

## The Leeuwin Current and larval recruitment to the rock (spiny) lobster fishery off Western Australia

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### Abstract

The phyllosoma larval stages of the western rock lobster (*Panulirus cygnus*) spend almost a year drifting in the south-eastern Indian Ocean, before metamorphosing to the puerulus stage and returning to the shelf. The pueruli settle in the coastal reefs where the juveniles remain for a period of three to five years and then recruit to the fishery.

Although previous studies have shown that there is a clear link between the Leeuwin Current and larval (puerulus) recruitment, the mechanisms which act on the larval stages or pueruli to bring this about are as yet unknown. This study of monthly larval settlement and environmental factors over the geographical range of the fishery between 1984 to 1989 shows that settlement along the coast of Western Australia follows a similar seasonal pattern at all sites and that there is a close correlation between adjacent sites. However, not all sites receive puerulus settlement annually, especially in the southern area of the fishery.

Cross correlation of Southern Oscillation Index, sealevel, sea surface temperature and salinity, with puerulus settlement at all sites indicates that similar processes are affecting larval recruitment along the whole coast. Comparison with a long series of data for a 20 year period from the central area of the fishery indicates that the correlations with sealevel from the 5-year data set are valid.

### Introduction

The catch of the western rock lobster (*Panulirus cygnus* George) fishery off Western Australia (Fig. 1) is largely taken between latitudes 28 and 32°S and has an annual value of about \$A200 million.

There are two distinct aspects of interest in recruitment to the fishery: the link between larval settlement and recruitment, and the factors responsible for variations in the level of puerulus settlement. First, the prediction of recruitment to the fishery is based on the demonstration that the commercial catch off Western Australia in any year is highly correlated with the level of puerulus settlement four years previously (Morgan *et al.* 1982, Phillips 1986). Second, the mechanisms contributing to the level of settlement need to be determined. There is, for example, a link between settlement and interannual variability in the flow of the Leeuwin Current, the anomalous poleward boundary current in the southeastern Indian Ocean (Pearce & Phillips 1988). However, the physical mechanism(s) responsible for the fluctuating levels of settlement are as yet unknown.

Current research by CSIRO is aimed at the second aspect, specifically a better understanding of the relationships between oceanic processes and the larval settlement in the coastal reefs as pueruli. This paper examines the results of a five year study of the spatial and temporal variability of puerulus settlement and environmental conditions over the geographic range of the fishery.

### Oceanic Part of Life Cycle

The life cycle of *P. cygnus* includes a nine to eleven month period in the southeast Indian Ocean. The larvae, which are flat and leaflike in shape, called phyllosoma, hatch in late spring or summer from females present on the outer edge of the continental shelf. They are transported out into the ocean, some of them up to 1500 km (Phillips 1981). The larvae remain at the phyllosoma stages for nine to eleven months during autumn and winter, increasing in size as they moult. At least nine phyllosoma stages are recognisable.

In late winter and early spring, the last phyllosoma stage transforms to a puerulus stage, which completes the oceanic cycle by swimming across the continental shelf and settling in the shallow limestone reef areas along the coast (Phillips *et al.* 1979, Phillips 1981). The settled puerulus stage moults into a small juvenile rock lobster. The peak settlement of pueruli occurs between September and January, following hatching in the previous November to February periods (Phillips *et al.* 1979).



Figure 1 Map of Western Australia showing the sites at which the puerulus stage of *Panulirus cygnus* were sampled.

### The Leeuwin Current

In autumn, winter and (to some extent) spring, the Leeuwin Current is evident in satellite imagery as a band of warm water sweeping southwards down the West Australian continental margin, around Cape Leeuwin and into the Great Australian Bight (Prata *et al.* 1986). In summer, by contrast, the flow is apparently much weaker. However, the satellite data show quite clearly that there is still a southwards-flowing stream during the summer months, so that there is a net southwards flow through the period of puerulus settlement between August and February, albeit with

intermittent periods of northwards currents especially near the coast (Boland *et al.* 1988).

The satellite imagery has also shown that the Leeuwin Current is a complex of jets, meanders and eddies. The meanders transport warm water some 100 km or more into the Indian Ocean, and then back towards the coast. Current measurements using satellite tracked buoys indicate that onshore current jets associated with these meanders can exceed 150 cm s<sup>-1</sup> or 3 knots (Pearce & Phillips 1992). Any phyllosomata entrained into this eastwards flow would be carried towards the shelf, where the transformation to puerulus and consequent settlement would presumably occur. Such oceanic features are often strongest in winter and early spring (at the start of the settlement period), perhaps providing one possible mechanism for returning pueruli to the shelf. Apart from these offshore features, the inshore boundary of the Current sometimes washes onto the shelf and brings warm Leeuwin Current water inshore, again possibly contributing to the settlement process. This may apply particularly in the southern areas because of the narrowness of the shelf.

Although the Leeuwin Current is a strong flow towards the south along the outer shelf and slope, currents along the central and inner shelf tend to reverse between northward and southward with a period of a few days (Cresswell *et al.* 1989). The mean drift is northwards at about 10 cm s<sup>-1</sup> in summer and southwards at 20 cm s<sup>-1</sup> in winter, but the oscillating currents can reach 50 cm s<sup>-1</sup> (1 knot).

### The Data

#### Puerulus

Phillips (1972) showed that the puerulus stage of *P. cygnus* can be captured with collectors composed of artificial seaweed moored at the surface within the protection of the coastal reefs. Subsequently, Phillips & Hall (1978) showed that sizes of catches from these collectors at each site provide a measure or index of the relative strength of settlement along the coast. Phillips (1986) used Seven Mile Beach as the "standard" site for the collection of puerulus data for catch prediction. Pueruli are collected at lunar monthly intervals. On occasion, therefore, two collections may be made in a calendar month: we have simply averaged the numbers of pueruli to give the settlement index for those months.

Pueruli indices used in this paper are from collectors deployed along the coast between September 1984 and December 1989. The nine sites were South Passage (Shark Bay), Horrocks Beach, Rat Island (Abrolhos), Seven Mile Beach, Jurien Bay, Cervantes, Alkimos, Warnbro Sound and Cape Mentelle (Kilcarnup) (Fig. 1). Logarithmic transformations were taken of the pueruli data.



Table 1

Correlation matrix of the logarithms of the monthly settlement indices at the nine sites between August 1984 and December 1989. SP = South Passage (Shark Bay); Hor = Horrocks Beach; Rat = Rat Island; SMB = Seven Mile Beach; Jur = Jurien Bay; Cer = Cervantes; Alk = Alkimos; WS = Warnbro Sound; CM = Cape Mentelle.

SP	1.000							
Hor	0.693	1.000						
Rat	0.620	0.784	1.000					
SMB	0.852	0.804	0.697	1.000				
Jur	0.816	0.739	0.707	0.861	1.000			
Cer	0.733	0.630	0.646	0.777	0.893	1.000		
Alk	0.571	0.614	0.555	0.756	0.740	0.710	1.000	
WS	0.595	0.506	0.403	0.668	0.661	0.724	0.825	1.000
CM	0.262	0.262	0.256	0.358	0.429	0.487	0.506	0.601
	SP	Hor	Rat	SMB	Jur	Cer	Alk	WS

A longer series of settlement indices covering 20 years at Seven Mile Beach and Jurien Bay (Phillips 1986) has also been used to check the validity of the conclusions from the five year series.

### Oceanography

A number of environmental variables have been analysed to examine correlations with pueruli settlement.

Monthly mean values of the Southern Oscillation Index (SOI), computed from the Darwin and Tahiti mean sealevel pressures (Troup 1965), were supplied by the Australian Bureau of Meteorology. Monthly mean sealevels for Fremantle were obtained from the Flinders University Tidal Institute in Adelaide. Because of the difficulty of obtaining reliable wind measurements along the coast due to "contamination" by coastal land/sea effects, we obtained from the Bureau of Meteorology daily winds in 2.5 degree squares off Geraldton. These have been vector-averaged for the monthly means.

Sea temperature and salinity have been measured at intervals of two to three weeks at a monitoring station in 55 m water depth near Rottnest Island since 1970 (with a few measurements made in earlier years). Samples are taken at 10 m depth intervals between the water surface and the seabed; monthly depth-averaged values have been used in this paper.

### Results

Correlations between the monthly (and total) puerulus settlement at the nine sites as well as cross correlations between the monthly puerulus settlement at the nine sites, SOI, sealevel, wind, water temperature and salinity have been undertaken.

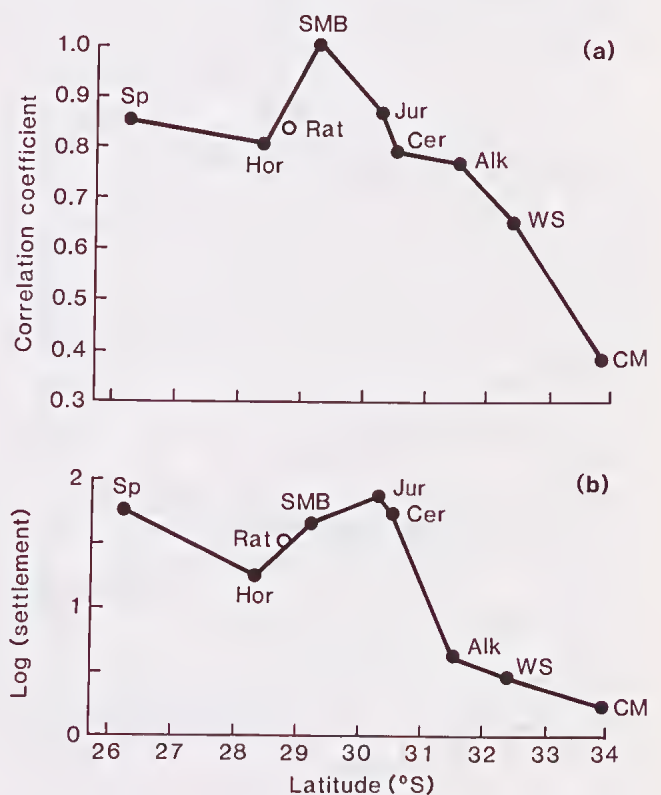


Figure 2 (a) Correlation of the monthly pueruli of *Panulirus cygnus* settlement from 1984-1989 at each of the 9 sites with that of the standard Seven Mile Beach site, after removal of the seasonal pattern. Rat Island has not been joined to the other sites by a line as that site is at the edge of the continental shelf, whereas all the others are on the coast. (b) Average pueruli settlement at each site over the full 64 month period.

Pueruli

The highest correlations of the monthly settlement (Table 1) were between Seven Mile Beach, Shark Bay, Horrocks Beach and Jurien Bay; Cervantes and Jurien Bay; and Warnbro Sound and Alkimos; whereas the correlations between Shark Bay, Horrocks Beach and Rat Island, and Cape Mentelle were low. The close correlation of the settlement at Rat Island, Jurien Bay and Seven Mile Beach was reported by Morgan *et al.* (1982). The correlation of the 20-year data set from Seven Mile Beach and Jurien Bay sites was high (0.804).

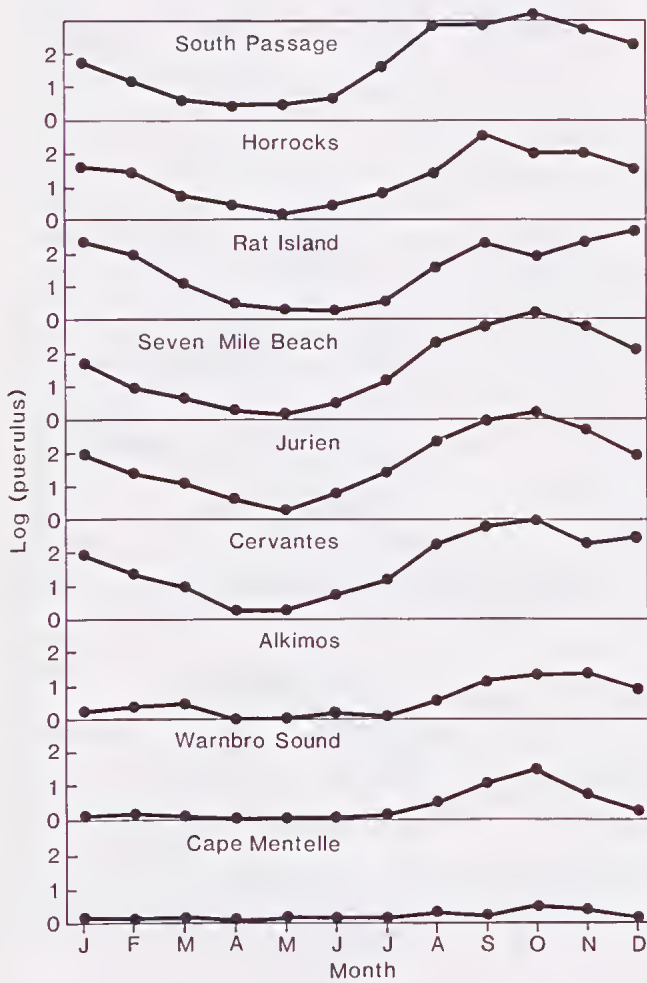


Figure 3 Monthly mean pueruli settlement (averaged over the 5 years) of *Panulirus cygnus* at each site.

Correlation of the monthly settlement over the 5-year period with the "standard" Seven Mile Beach site (Fig. 2a) shows that the correlation decreases with distance from that location: the correlations are significant at the 99% level at all sites. The average settlement levels at the nine sites over the 5-year period (Fig. 2b) show a similar picture; with the highest levels of settlement occurring at Shark Bay, Jurien Bay and Cervantes, and that all these were higher than Seven Mile Beach while from the Alkimos southwards the settlement is generally low.

The mean seasonal pattern of puerulus settlement along the coast over the 5-year period 1984 to 1989 is shown in Fig. 3. Peak settlement tends to occur at all sites between August and December. Cross correlation (ccf) of the settlement at Seven Mile Beach with the other eight sites indicates that there is a tendency for settlement one month earlier at Cape Mentelle than Seven Mile Beach (ccf = 0.37), and one month later at Rat Island (ccf = 0.84). In some years, settlement began earlier in the season, or extended well into the following summer.

Pueruli anomalies

For all the datasets used in the further cross correlation analyses, the annual cycle has been removed, and the statistical analyses are therefore using the anomalies from the monthly means to check for association of one series with lags of another. The test statistics for cross correlations are only valid if each of the series has a zero autocorrelation function. Six of the nine puerulus series have significant autocorrelation functions as do three of the five environmental series. Therefore there are few valid tests. Diggle (1990) suggests the approximate formula  $2/\sqrt{n}$  ( $= 0.25$  in our case), where  $n$  is the total number of months, to assess the significance of the cross correlation function and the significance levels indicated are by this method. Due to the number of variables and the number of different lags being examined there may be some "significant" correlations which may be spurious.

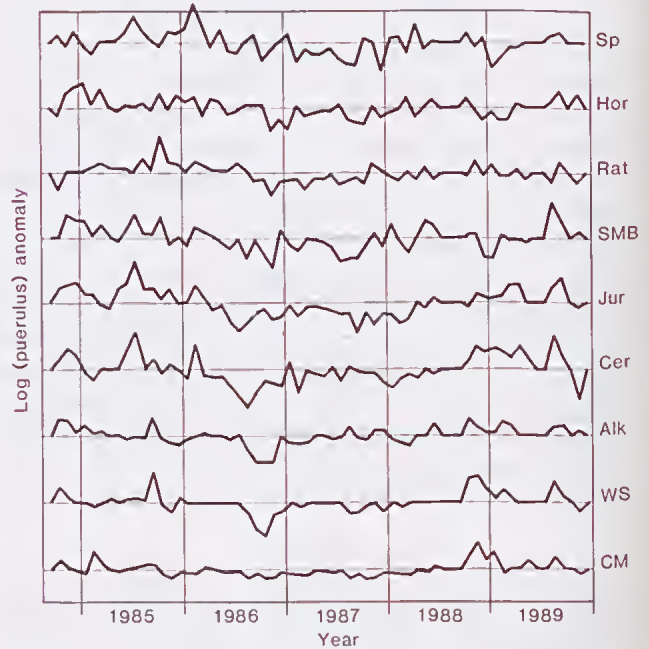


Figure 4 Anomalies in monthly pueruli settlement of *Panulirus cygnus* at the 9 collector sites between August 1984 and December 1989. The vertical axis is the logarithm of the settlement.



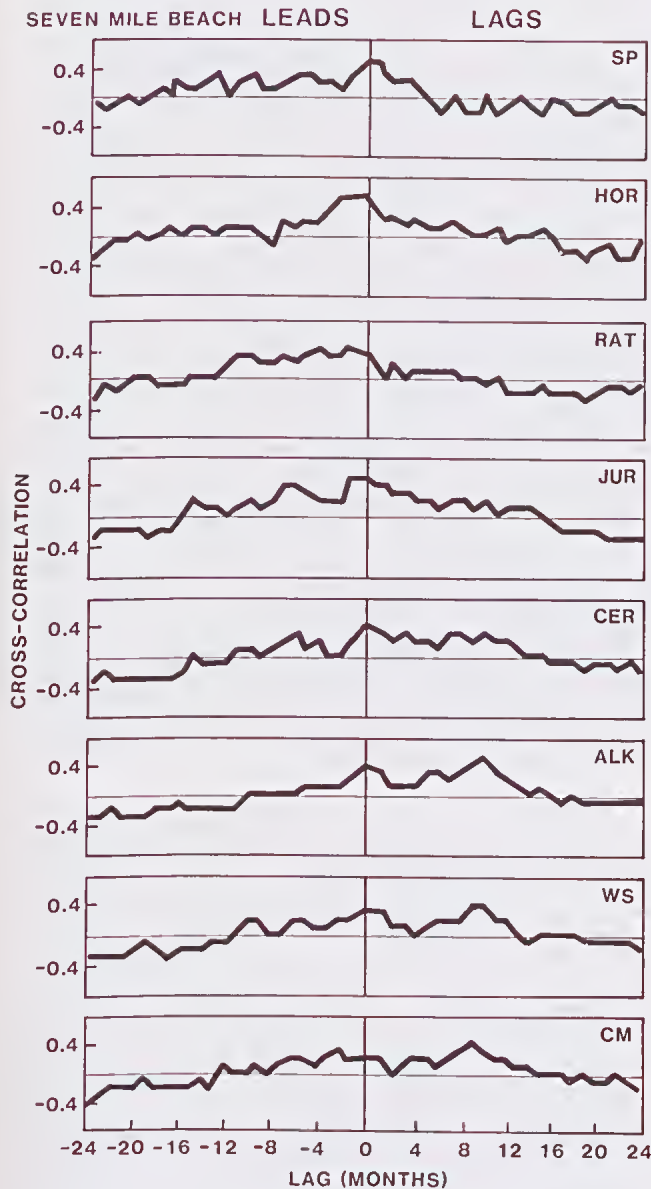


Figure 5 Cross correlations of pueruli of *Panulirus cygnus* at the 8 sites along the coast of Western Australia with the standard Seven Mile Beach site.

The anomalies in monthly settlement at the nine sites over the five year period 1984 to 1989 show both the alongshore and temporal variability in settlement (Fig. 4). The cross correlations of the anomalies in monthly settlement between Seven Mile Beach and the other eight locations (Fig. 5) indicate that there are different lag times in settlement with zero or short lags of two or four months in the northern sites from Shark Bay to Cervantes; versus longer lags of nine to ten months at the southern sites, Cape Mentelle, Warnbro Sound, Alkimos. The anomalies at Cape Mentelle, Warnbro Sound, Alkimos precede the Seven Mile Beach anomalies by 9-10 months. For example, the troughs in settlement that occurred late 1986 at Warnbro Sound, Alkimos and Cervantes do not occur

till late 1987 in Seven Mile Beach, Horrocks Beach and Shark Bay (Fig. 4); and the peaks in Cape Mentelle, Warnbro Sound and Alkimos that occurred in late 1988 did not occur till late 1989 in Jurien Bay, Seven Mile Beach and Horrocks Beach. However, one must bear in mind that neighbouring locations are correlated and so a peak in one series is likely to be accompanied by peaks in the neighbour.

#### Pueruli and environmental variables

The maximum cross correlations and lags between the pueruli monthly series for 1984-1989 and the environmental series are shown in Table 2. The cross correlations of pueruli with wind (both north-south and east-west components) are low. The cross correlations of pueruli and SOI, Fremantle sealevel, Rottnest water temperature and salinity are all significant. The highest cross correlation was Cervantes pueruli one month after water temperature. Other high cross correlations are Jurien Bay pueruli three months after SOI or sealevel, one month after water temperature and zero lag with salinity.

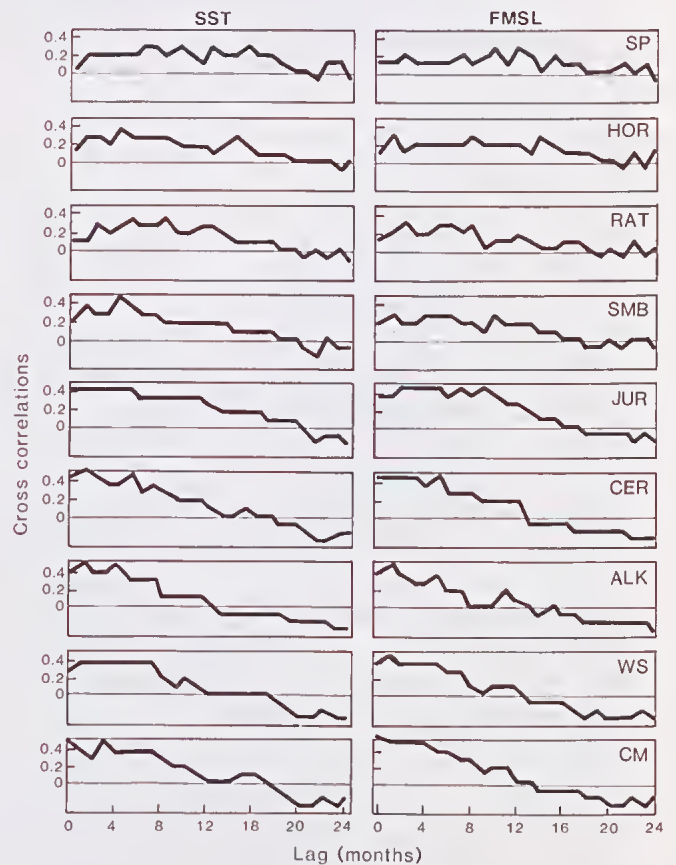


Figure 6 Cross correlations of pueruli settlement of *Panulirus cygnus* with Fremantle sealevel (FMSL) and water temperature (SST).

The cross correlation functions of pueruli for 1984-1989 with sealevel and water temperature are shown in Fig. 6. There was a broad trend of smaller lags (1-3

Table 2

The maximum cross correlations of pueruli with the environmental series (seasonal effects removed) showing maximum lags.

	SOI		Sealevel		SST		Salinity		East wind		North wind	
Site	max cross corr	lag (mths)	max cross corr	lag (mths)	max cross corr	lag (mths)	max cross corr	lag (mths)	max cross corr	lag (mths)	max cross corr	lag (mths)
SP	.23	3	.32	10	.33	9	-.33	15	-.26	0	.24	0
Hor	.24	8	.32	8	.38	4	-.37	1	-.29	6	-.23	8
Rat	.35	0	.30	8	.43	9	-.24	5	-.21	1	-.27	8
SMB	.27	3	.29	10	.53	4	-.37	6	-.36	3	-.29	8
Jur	.51	3	.51	3	.51	1	-.57	0	.17	6	-.28	4
Cer	.49	3	.50	3	.62	1	-.48	0	.27	11	-.42	1
Alk	.30	1	.50	1	.50	4	-.38	0	.25	5	-.35	3
WS	.43	1	.47	1	.45	1 or 5	-.31	0	.21	5	-.37	3
CM	.50	3	.56	0	.46	3	-.52	0	.19	4	-.34	4

months) for the southern sites (Cape Mentelle, Warnbro Sound, Alkimos, Cervantes, Jurien Bay), with sealevel and water temperature to larger lags (4-10 months) for the northern sites (Seven Mile Beach, Rat Island, Horrocks Beach, Shark Bay). This trend is also evident with salinity.

A similar cross correlation analysis of the longer time settlement data from Seven Mile Beach and Jurien Bay against sealevel showed that the maximum cross correlation (0.27) occurred when settlement at Jurien Bay lagged Fremantle sealevel by four months and when Seven Mile Beach lagged Fremantle sealevel by four months (0.26).

#### Satellite imagery

We also attempted to relate mesoscale (order 100 km) features of the Leeuwin Current as revealed by satellite images to fluctuations in puerulus settlement along the coast. Pearce & Phillips (1988) suggested, for example, that a strong meander off Geraldton in October 1984 may have contributed to the record settlement at Seven Mile Beach in that month.

While there is little doubt that meanders offshore of the Leeuwin Current can rapidly bring phyllosoma larvae towards the shelf (Pearce & Phillips 1992),

current measurements along the shelf break have shown that the alongshore flow is very strong (Cresswell *et al.* 1989). It now seems more likely, therefore, that the pueruli will be carried both south and north by the reversing current system on the shelf and so distributed over a larger area of coastline.

Along the inshore boundary of the Current, settlement may be aided or hindered by variations in the currents or water temperature near the coast. For example, zero settlement at Cape Mentelle in 1986 and 1987 (both ENSO years when low coastal sealevels indicated a weak Leeuwin Current) was possibly associated with the Leeuwin Current being along the outer shelf and a cool inshore counter-current in that area (Fig. 7a). In 1988, on the other hand, there was appreciable settlement at Cape Mentelle, and satellite imagery for November 1988 showed warm Leeuwin Current water flooding onto the shelf (Fig. 7b).

#### Discussion

##### Spatial and temporal settlement of puerulus

It is clear that settlement along the coast of Western Australia follows a similar seasonal pattern at all sites and that in years when settlement occurs there is a close correlation between adjacent sites. However, the



Figure 7 Satellite images of South-Western Australia from the NOAA Advanced Very High Resolution Radiometer (AVHRR): (upper) orbit N9/15219 on 26 November 1987, and (lower) orbit N11/646 on 9 November 1988. The Leeuwin Current is evident as the warm (pale) water along the shelf. The area shown is from Fremantle (in the north) to south of Cape Leeuwin; Cape Mentelle is midway between the two prominent capes (Cape Naturaliste and Cape Leeuwin). Images courtesy of the Western Australian Satellite Technology and Applications Consortium (WASTAC).



southern sites receive lower levels of settlement than in the north, and in some years have zero settlement.

Both 1986 and 1987, the two years in which no settlement was recorded at the southern sites, were ENSO years when the Leeuwin Current was weaker. Settlement to the southern area may only occur (or be higher) when the Leeuwin Current is strong and running close inshore. Catches in the southern area of the fishery fluctuate much more than in the central and northern areas of the fishery, supporting this hypothesis.

#### Correlation between environmental events and levels of pueruli settlement

Only preliminary conclusions can be drawn from the results in view of the short time span of the data. Phillips (1986) recorded fluctuations in the annual index of puerulus settlement at Seven Mile Beach ranging from 15.9 to 182.8 over a 14-year period. Between 1984 and 1989 the values ranged from 60.3 to 128.4, hence it is difficult to assess the exact reliability of the cross correlations recorded. However, the strong cross correlations of SOI, sealevel, sea surface temperature and salinity with settlement at all sites indicate that similar forces are affecting settlement along the whole coast. This is in line with the conclusions of Pearce & Phillips (1988) who suggested that the oceanic processes influencing settlement along the Western Australian coastline operate at length scales of the order of hundreds of kilometres and time scales of many months to a year.

Of the environmental factors examined in this study, sealevel, sea surface temperature and salinity may all reflect interrelated expressions of monthly to annual variations in the strength or temperature of the Leeuwin Current.

Some of the correlations are curious. It is, for example, difficult to imagine the basis for the between-season time lags of puerulus settlement where the northern sites, such as Seven Mile Beach, follow settlement at the southern sites nine to ten months later. However, the long term (20-year) data from Seven Mile Beach and Jurien Bay show the same picture. This may point to previously unrecognised linkages in oceanic events.

Although Pearce & Phillips (1988) demonstrated that there is a clear link between the Leeuwin Current and larval recruitment, the mechanisms which act on the larval or puerulus stage to bring this about are as yet unknown. This is partly because of a lack of

information about the site of transformation to, and the behaviour of, the puerulus stage, as well as variability of the oceanic environment. Further studies of both these aspects are necessary.

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